Semiconductor nano materials-Graphene

Outlines:

1. Introduction of Graphite
2. Structure of graphene
3. Properties of graphene
4. Applications of graphene

Prerequisite/Recapitulations

Knowledge of crystal structure and bondings in solid

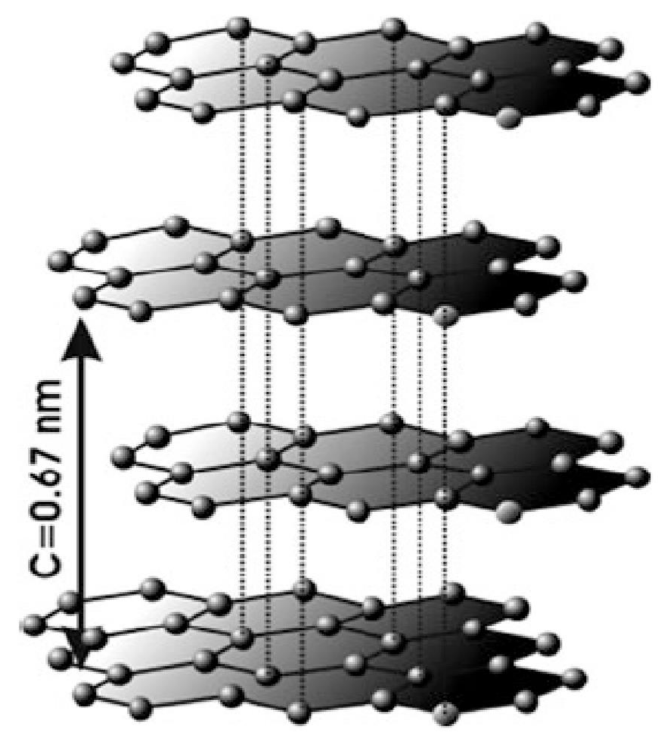
Objectives

After the completion of this lecture, you will be able to:

1. **Explain the structure of graphene**
2. **Understand the properties of graphene**
3. **Learn the different applications of graphene**

Graphite:

Graphite is allotrope of carbon having a layered structure of sp^2 bonded sheets held together by weak Van der Waals bonds (Fig. 3). The individual sheets are of honeycomb structure with C–C sp^2 bond length 0.142 nm and all the atoms lying in one plane. The interlayer separation is about 0.335 nm and the unit cell c axis has length 0.67 nm. Due to the weak bonds holding these layers together, the layers are able to slide over one another upon application of shearing stress and thus graphite is able to provide good lubricating action in certain applications. Depending on the relative stacking of the layers, graphite can be alpha (hexagonal) or beta (rhombohedral) phase.

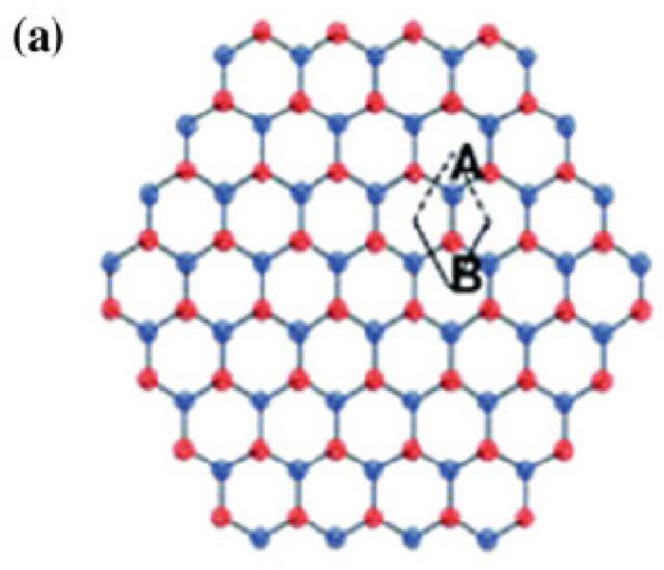


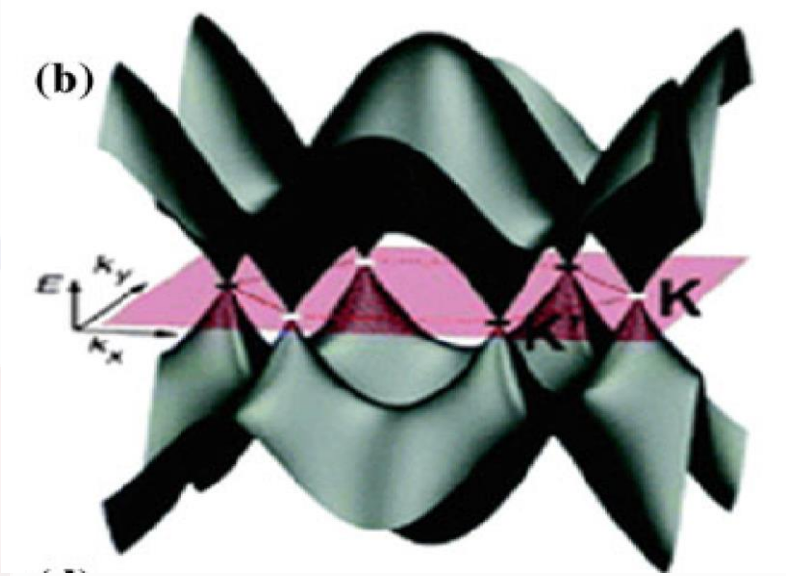
The structure of Graphene

Graphene

The individual freestanding honeycomb layers of graphite when chemically/ mechanically exfoliated from the bulk show remarkably different properties than the bulk graphite. First, in such a material the carriers are effectively confined in one direction (e.g., z) and are free to move in the other two (x–y). This gives rise to quantum confinement in the (say z) direction. The carriers in such a material have only 2 degrees of freedom and therefore such materials are known as 2D materials. Graphene, Silicene, Germanene, monolayer transition metal dichalcogenides (TMDs), and phosphorene etc., fall in this category of materials. The first free-standing Graphene was discovered in 2004 by A.K. Geim and K. Novoselov, by the famous scotch tape method (also known as mechanical exfoliation) from bulk graphite. Since then, several other methods including chemical exfoliation, chemical vapor deposition, micromechanical cleavage, epitaxy and reduction of Graphene oxide have been also adopted for Graphene fabrication. Owing to the discovery of a new class of materials, Geim and Novoselov were awarded the 2010 Nobel Prize in Physics. Graphene, a 2D material is an sp2-bonded honeycomb of carbon atoms lying in the same plane. The C–C bond length in Graphene is 0.142 nm and the unit cell of Graphene is made up of two carbon atoms (labeled A and B) in the Fig 4. The unit cell is an equilateral parallelogram with sides 0.246 nm.

Graphene

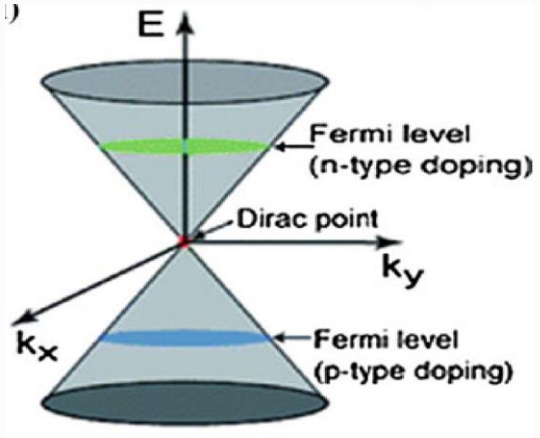




Hexagonal honeycomb lattice of Graphene with two atoms (a and b) per unit cell. (b) The 3D band structure of Graphene.

Graphene

The most interesting property lies in the band structure of Graphene. The valence and conduction bands of Graphene touch each other at the six K points of the Brillouin zone making it a zero band gap material and giving it exceptional electrical and thermal conduction properties. The fact that the valence (VB) and conduction bands (CB) touch each other at these K points of the BZ (which are also known as Dirac points for Graphene Fig.) lead to the advantage of charge pumping from VB to CB without having to overcome any band gap. Therefore, intrinsic Graphene has a very high amount of carrier density, which corresponds to a value of ~$10^{10}/cm^2$ at room temperature. Such huge availability of carriers makes Graphene an excellent conductor. Free-standing sheets of Graphene show doping-independent high carrier mobility of over 200 $cm^2\ V^{-1}\ s^{-1}$ (carriers in Graphene are considered to be massless Dirac Fermions). Further, it is optically transparent and highly flexible but stronger than steel.

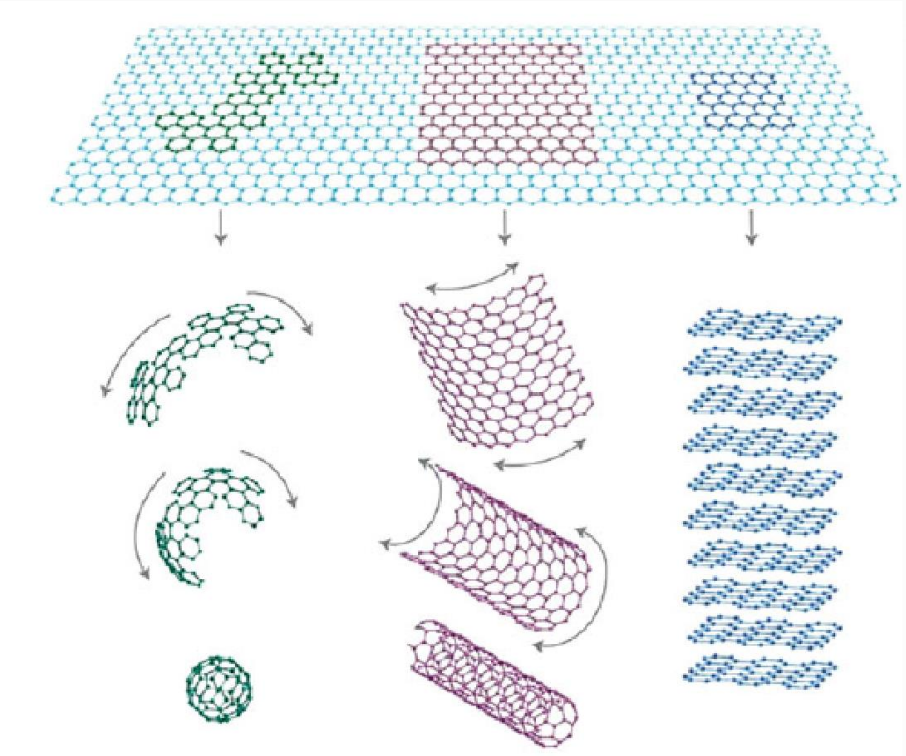


Approximation of the low-energy band structure as two cones touching at the Dirac point. The position of the Fermi level determines the nature of the doping and the transport carrier.

Properties of Graphene:

Properties of Graphene:

1. Graphene is only one-atom thick, it is considered to be a two-dimensional material.
2. Zero band gap
3. Low resistivity about 10^{-6} Ω-cm (less than silver).
4. High electron mobility (≥15,000 $cm^2\ V^{-1}s^{-1}$).
5. Despite being the thinnest material known to exist, it is also the strongest material ever tested—100 times stronger than steel.
6. The electronic properties of this leads to, an anomalous quantum Hall Effect.
7. High mechanical strength than steel (100 times)
8. Optically transparent to visible radiation (97.7 %).



Graphene is a 2D building material for carbon materials of all other dimensionalities. It can be wrapped up into 0D buckyballs, rolled into 1D nanotubes or stacked into 3D graphite.

Properties of Graphene:

Optical properties: Graphene is almost transparent; it absorbs only 2.3% of the light intensity, independent of the wavelength in the optical domain. This is thin, mechanically strong, transparent and flexible conductor. It can be used in touch screen, light panel, solar cells (ITO) and flexible display. Graphene is visible through feeble interference effect. Different thicknesses are show different colors.

Thermal properties: The thermal conductivity of Graphene is dominated by phonons and has been measured to be approximately 5000 $Wm^{-1}K^{-1}$. Copper at room temperature has a thermal conductivity of 401 $Wm^{-1}K^{-1}$. Thus Graphene conducts heat 10 times better than copper.

Mechanical properties: The Young's modulus of few-layer Graphene was experimentally investigated with force-displacement measurements by atomic force microscopy (AFM). Graphene is as the strongest material ever measured, some 200 times stronger than structural steel.

Application of Graphene

Solar cell- With high electrical conductivity, high carrier mobility, and moderately high optical transmittance in the visible range of the spectrum, Graphene materials show promise for transparent conductive films used as substrate for solar cell.

Photovoltaic devices- Due to its high optical transparency and high conductivity it is used as substrate electrode in photovoltaic devices. This can replace ITO based electrode.

Sensors- Due to its conductance changing as a function of extent of surface adsorption the monolayer Graphene is a promising candidate to detect a variety of molecules, such as Gases to biomolecules.

Charge transfer between the adsorbed molecules and Graphene is proposed to be responsible for the chemical response. As molecules adsorb to the surface of Graphene, the location of adsorption experiences a charge transfer with Graphene as a donor or acceptor, thus changing the Fermi level, carrier density, and electrical resistance of Graphene.

Clean energy conversion devices- There have been several reports on Graphene-based electrodes for both rechargeable lithium ion batteries (RLBs) and electrochemical double layer capacitors (EDLCs)

Other application- Mobile and computer touch pad screens, Flexible electronic components, Transistors, replacing silicon based materials, electrochemical sensor and biosensors.

Questions

- **Explain the structure of Graphite**
- **Describe the structure of graphene**
- **What are the properties of graphene?**
- **Describe the various applications of graphene**

References

1. J. Singh , Semiconductor optoelectronics, Physics and Technology, Mc-Graw –Hill Inc.
2. S.O. Pillai , Solid State Physics, , New Age International (P) Ltd. Sixth edition, 2010.
3. S.M. Sze, Semiconductor Devices: Physics and Technology, Wiley 2008.
4. Introduction to Nanotechnology C P Poole, Frank J. Owens, John Wiley & Sons, 2011.
5. Introduction to Nanoscience and Nanotechnology, KK Chattopadhyay, A N Banerjee, Phi Learning Pvt Ltd., New Delhi, 2012.
6. www.nano.gov/nanotech-101/special
7. https://www.youtube.com/watch?v=1QwyMWM0Jjg